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Energy efficiency and desalination in the Canary Islands

Julieta Schallenberg-Rodríguez*, José Miguel Veza, Ana Blanco-Marigorta

Department of Process Engineering, Universidad de Las Palmas de Gran Canaria, Las Palmas, Spain

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ABSTRACT

Faced with the challenge of meeting high water and energy demands with no conventional energy resources and a lack of potable water, the Canary Islands have been using desalination plants for nearly 50 years. The first desalination plant in Europe was installed in 1964 in Lanzarote. Today, desalination capacity in the islands stands at over 600,000 m^3/d (covering 55% of water demand). Powering the plants consumes nearly 12% of total electricity demand at a cost of over 200 million Euros yearly. Though desalination continues to be the main way of meeting water demand, its major drawback is the strong dependence on conventional energy. The islands have always looked for reducing the energy consumption in desalination processes. This paper describes the relationship between energy and desalinated water and its evolution in the islands over the past 50 years, examining the trends in energy efficiency and the technological changes in the desalination systems, which also explains the predominance of reverse osmosis plants in the current scenario. A series of case studies describe various challenging desalination projects (including operating data) that have been installed in the Canary Islands.

Contents

Abbreviations: GDP, Gross Domestic Product; RES, Renewable Energy Sources; PV, photovoltaic; MSF, multi-stage flash; ME, multi-effect; VC, vapour compression; RO, reverse osmosis; ED, electrodialysis; BAT, best available technology; ER, economy ratio; ERD, energy recovery device; ERI, energy recovery incorporated; PES, pressure exchange system; hm^3, cubic hectometer (1 million m^3)

* Corresponding author.
E-mail address: jschallenberg@dip.ulpgc.es (J. Schallenberg-Rodríguez).

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1. Energy-water in the Canary Islands

The Canary Islands is a Spanish Archipelago located in the subtropical area. The Islands have no electrical grid connection with mainland and are highly dependent on external energy sources. At the same time, fresh water production is scarce in the islands and it is not enough to serve its population.

1.1. Water situation in the Canary Islands

The Canary Archipelago is a part of Spanish national territory and is comprised of seven main islands: Lanzarote, Fuerteventura, Gran Canaria, Tenerife, La Palma, La Gomera and El Hierro. The Archipelago is located off the Western Sahara (parallel 28) in the subtropical area.

The characteristics shown in Table 1, particularly the strong impact of the tourist industry and its associated fresh water needs, explains the huge water demand.

The seven Canary Islands are known as the "Fortunate Islands" partly because of their year round temperate climate, but nowadays they are far from fortunate in terms of water resources. On average, there are less than 300 m^3 of water available (including natural water resources and desalinated water) per inhabitant and year, whereas continental Spain has 1113 m^3 per inhabitant and year, a value which is in turn low in comparison with most other European countries. More importantly, the vast majority of these water resources are underground and very difficult to extract [1].

To reach these groundwater resources, the Canary people historically relied on ingenuity and hard work. In the 19th century, landowners and farmers started digging wells and horizontal galleries (similar to gold or diamond mines) to mine water. They initially dug near the sea but, as the more accessible waters were extracted, they were forced to go further and deeper to meet the rapidly increasing demand. Consequently, aquifers dwindled: whereas 100 m long galleries were sufficient in 1900 to find water, the average length in 2000 was between 3.5 and 4.5 km and some galleries were up to 6 km long [1]. Things had come to such a pass by this time that, in islands like Gran Canaria, the groundwater level was falling 20 m yearly, forcing the digging of wells of up to 600 m [2]. The public sector started to invest massively in desalination, as they did not believe that groundwater resources, even if managed in a sustainable way, would be sufficient to meet the increasing demand [1].

Today, water desalination in the Canary Islands is more than merely a technique for water treatment. For the last 50 years, it has been a means of continued existence for many communities.

Table 1
The Canary Islands: some data of interest.

No. of islands	7
Population	2.2 Million
Tourists per year	12 Million
Surface	7447 km^2
Coastline	1531 km
Average rainfall per year	300 mm
Water consumption	470 hm^3/y

No electricity grid connection with mainland Each island generates its own electricity No conventional energy resources.

Indeed, the survival of the islanders and the maintenance of their living standards cannot be conceived without desalination. Desalination is a vital cog in the human and financial activities of the Archipelago. It is difficult to imagine how life in the Canary Islands would have been without the extensive application of the different desalination techniques. In the past, islands with almost no ground or underground water resources (like Lanzarote and Fuerteventura) were supplied by water tank vessels from the Navy. The remaining islands used mainly their underground waters. It can justifiably be argued that the rise in population, the growth of the tourist sector and the development of agriculture would have been impossible without desalination technologies [3]. For example, the natural water resources of Fuerteventura (mainly brackish underground water), an island with a population of 110,000 inhabitants, are barely sufficient to meet the demands of a population of 10,000 [2]; less than 10% of its current population. In the case of Lanzarote, the island that most strongly depends on desalination, 99% of consumed water comes from desalination plants.

Currently, desalination capacity in the Canary Islands is about 600,000 m^3/d, representing around 1% of total worldwide desalination capacity [4]. In 2010, total water consumption in the islands was 470 hm^3 , 55% of which (260 hm^3) came from desalination [5]. This percentage of 55% desalinated water has remained more or less constant for the last decade.

1.2. Energy situation in the Canary Islands

The Archipelago is highly dependent on external energy sources. Nearly 98% of primary energy consumption is based on imported oil brought to the islands by ships. In 2012, 93% of electricity production came for these sources [6]. Though the Canary Islands have no conventional energy sources, there is a lot of potential for the exploitation of renewables, mainly wind and solar.

As a result of the geographical distance between the Canary Islands and the European mainland there is no electrical grid connection between the former and the latter. The only submarine cable is of limited power and lies between the islands of Lanzarote and Fuerteventura. The seven islands are powered using six autonomous weak electrical grids. Given the lack of conventional energy resources, it can be stated that there is total external energy dependency [7].

Total installed electrical power in the Canary Islands at the end of 2012 was 3163 MW, 11% of which was from renewable energies, though in production terms this value falls to just 7% [6]. The RES (Renewable Energy Sources) used in the Canary Islands are mainly wind and solar photovoltaic, 145 MW and 162 MW respectively in 2012 [6]. Most of the PV power was installed on land (PV farms) and only a small percentage on rooftops.

One of the priorities of the islands is to increase the level of energy self-sufficiency. This can only be done by deploying RES to reduce conventional energy dependency. RES deployment can also actively contribute to foster employment and to encourage regional development [8]. For the year 2015, the Canary Islands Energy Plan has determined that 30% of the electricity generation should be supplied by RES, mainly wind and solar. Wind energy should reach 1025 MW, photovoltaic 160 MW and wave energy 50 MW [9].

Since water production in the Canary Islands is highly dependent on the shipping of imported oil, the reduction of conventional

energy consumption in desalination plants is crucial. The evolution of desalination technologies in the Archipelago has to be understood in this context of a continuous need to reduce conventional energy consumption.

2. Evolution of desalination (and its energy consumption) in the Canary Islands

2.1. Introduction

Energy consumption in desalination plants depends mainly on two factors: the technology used and the water type. Two types of feed water are utilized in the Canary Islands: seawater and brackish water (from underground wells). The technologies used can be divided into two main groups: distillation and membrane.

Distillation plants can be classified into three different systems: multi-stage flash (MSF), multi-effect (ME) and vapour compression (VC). The first two (MSF and ME) are usually dual plants, producing water and electricity at the same time. Distillation plants can also be classified by size, with MSF and ME the largest-sized units (thousands of m^3/d) and VC units comparatively smaller (installed mostly in hotel resorts).

Membrane plants utilize two different technologies: reverse osmosis (RO) and electrodialysis (ED). The latter (ED) is not suitable for seawater, due to its high salinity, but has been widely used for brackish water.

All these different technologies have been installed in the Canary Islands to varying extents and at different times. A description of the operation of these technologies can be found in e.g. [10].

The first desalination plant in the Canary Islands was installed in 1964 in the island of Lanzarote and had a capacity of 2300 m^3/d. At the present time, total desalination capacity is approximately 600,000 m^3/d and all the islands have desalination units except for one, La Palma, which still uses underground water to cover all its demand. This total production capacity is diversified in all kinds of processes and plants of varying size and capacity. For the purposes of this paper, the plants themselves have been defined as large-sized (bigger than 10,000 m^3/d) and small/medium-sized.

On an annual basis, desalination production in the islands is about 260 hm^3 (2010 data) [5]. This entails an approximate electricity consumption of more than 1000 GWh per year (considering an average consumption of 4 kWh/m^3). If we compare this to total electricity consumption in 2012 of about 9000 GWh, the electricity consumed for desalination purposes represents nearly 12% of total electricity demand and is equivalent to an annual expenditure of 230 million Euros (more than 600,000 Euros each day), considering an average electricity cost in the Canary Islands of 220 €/MWh in 2012 [6].

The reliance of desalination on conventional energy sources has meant the need for continuous improvements in the energy efficiency of desalination plants. Table 2 shows the evolution of energy consumption (in kWh/m^3) for the best available technology (BAT) over the last 35 years.

Desalinated water satisfies the needs of more than 1 million inhabitants and almost all tourists visiting the islands.

Table 2
Evolution of specific energy consumption (BAT)..

Year	Energy consumption BAT (kWh/m^3)
1975	22[a]
1980	17[a]
1985	14[a]
1990	9[a]
1995	5[a]
2000	2.9[a]
2012	2.0[b]

[a] [11]
[b] [4].

2.2. From the first desalination unit to the 90s

As previously mentioned, the first seawater desalination plant in Europe was installed in 1964 in the island of Lanzarote with a capacity of 2300 m^3/d and used MSF technology. This technology was also used in the second and third desalination plants in the islands, which were both dual plants producing water and electricity at the same time. The Las Palmas I plant was built in 1969 in Gran Canaria with a capacity of 20,000 m^3/d and 20 MW of electrical power. The third plant was built in 1970 in Fuerteventura and had a capacity of 20,000 m^3/d and 700 kW.

The first VC plant was built in 1972 in Fuerteventura. It had a capacity of 600 m^3/d and was installed in a hotel, serving the tourists of the resort. In the following years, a number of VC units were built, mainly in tourist resorts, varying from 50 to 1500 m^3/d.

At the end of the 70s, the first RO unit was built in Fuerteventura. It was an 80 m^3/d brackish water plant for agriculture purposes. In 1983, the first seawater RO plant was built in Lanzarote with a capacity of 500 m^3/d. In 1986, the first ED plant was built in Gran Canaria with a capacity of 22,000 m^3/d and a specific energy consumption of 3.5 kWh/m^3 [12]. Its feed water came from several underground wells located nearby (brackish water).

2.3. Status in 1990

By 1990, all the technologies in use in the islands, except for ME, had been installed in the Archipelago. The three easternmost islands, Gran Canaria, Fuerteventura and Lanzarote all had desalination plants for both brackish and seawater. Total installed desalination capacity at that time was 212,000 m^3/d, including 39,000 m^3/d of brackish water [13].

2.3.1. Brackish water

By 1990, there were 50 RO units for brackish water and 2 ED units, accounting for 16,800 m^3/d and 22,100 m^3/d respectively. These figures reflect the relatively small size of the brackish water RO units in comparison to the ED ones. Electricity consumption for these brackish water plants ranged from 1.5 to 4 kWh/m^3, with an average consumption of 3.2 kWh/m^3. No energy recovery system had been installed due to the low operating pressure and the small size of the units. The ED plants operated at below 10 bar and most of the RO units below 30 bar (except for 8 units working between 30 and 40 bar) [13].

2.3.2. Seawater

In 1990, seawater desalination capacity was 173,000 m^3/d, distributed between MSF (27%), VC (19%) and RO (54%).

The two distillation systems operated at relatively high temperatures (MSF at between 90 and 120 °C and VC at between 60 and 70 °C) and required high energy consumption. Average recovery ratio was 45% (similar to RO) and average energy consumption of the VC plants (38 units in total) 13.2 kWh/m^3.

The RO plants (28 units in total) operated at an average pressure of 68 bar. Average recovery ratio was 44% (slightly lower than in distillation plants), while average energy consumption was much lower than in distillation systems at 5.92 kWh/m^3.

The newest and biggest RO plants began to integrate energy recovery systems incorporating Francis turbines [13].

This difference in energy consumption was one of the main reasons that led to the definitive shift to RO, which is presently the leading technology.

2.4. From the 90s to 2000

The overdrawing of aquifers was reducing underground water reserves, particularly in Gran Canaria. Consequently, most of the new desalination plants in this decade used seawater as feed, even for agriculture purposes. Regional administration policy opposed new underground brackish water extractions for desalination. A government programme was developed aimed at providing desalinated water to all inhabitants living below 300 m altitude in the three eastern islands [12].

In 1992, the first large RO plant was built with a capacity of 36,000 m^3/d and a turbine-based 26% energy recovery system. In 1994, the first ME plant was built in Tenerife with a capacity of 3600 m^3/d. Construction of the second ME plant (and the first large-sized unit) was completed in Gran Canaria (Las Palmas-Telde) in 2000. It had a capacity of 35,000 m^3/d [12].

Table 3 shows the evolution of energy consumption of all large-sized distillation plants (MSF and ME) installed in the Canary Islands up to 2000. Energy consumption is expressed as “Economy Ratio” (ER), which is the usual figure for distillation units. ER expresses the kilograms of product water obtained per kilogram of vapour. Thus, the higher the ER, the higher the efficiency of the system.

No large-sized distillation plants have been installed since 2000 probably due to their high energy consumption, though other factors may also be relevant.

MSF plants are dual plants, which means that they are high capacity units that have to be installed where both fresh water and electricity are needed. MSF plant energy consumption is the highest of all the technologies used on the islands. Since a higher brine temperature means higher energy efficiency, the maximum attainable brine temperature limits energy efficiency in these plants. However, an increase in brine temperature also means an increase in scale formation and other problems related to high salinity and temperature, making it difficult to exceed a brine temperature of 120 °C. It can be seen in Table 3 how ER varies with temperature, rising from 6 to 10 as brine temperature changes from 90° to 120 °C.

In the case of ME plants, energy efficiency is proportional to the number of effects (stages), which is also limited to a certain degree. It can be seen in Table 3 how ER is around 11, higher than in MSF plants.

During this decade, several VC plants were installed in the islands, mostly for tourist resorts. Their energy consumption varied from 8.3 to 11 kWh/m^3, more than half the 22 kWh/m^3 energy consumption of the first units back in the 70s [12]. This fall in energy consumption was mainly due to improvements in heat transfer and compressor design [14].

However, in terms of energy consumption none of these technologies could compete with RO plants. Since the introduction of RO in the islands, at the end of the 70s, manufacturers, project managers and maintenance companies worked continuously on improvements to the RO membranes, high-pressure pumps, energy recovery systems, etc. Most of the plants built in the Canary Islands between 1990 and 2000 used RO technology, either for sea- or brackish water. RO modules allow plants to be assembled in a wide size range: from 50 m^3/d to 36,000 m^3/d.

In their pursuit of energy consumption reductions, plant owners analysed and in many cases replaced or modified the energy recovery system. The usual arrangement in RO plants during this decade was a high-pressure pump and an energy recovery device (ERD). Centrifugal high-pressure pumps were commonly used, with efficiencies between 75% and 85%. Smaller plants (below 50 m^3/d) tended to install positive displacement pumps. Since the early 90s, all medium- and large-sized plants were fitted with ERDs. These devices took advantage of the high pressure existing in the brine, using it to drive the pump and thereby reduce the net power demand. Many plants were built in this decade using a two-stage design in order to improve energy recovery. For some time the available devices were centrifugal turbines, running as reverse pumps (efficiencies up to 77%). During the second half of the decade, Pelton turbines became popular due to their higher efficiency (over 87%). The refurbishment of many plants over this period allowed the installation of ERDs. Other experimental improvements included devices that incorporated the joint operation of pumps and recovery turbines.

Due to improvements in hydraulic design (higher pump and turbine efficiencies, reduction of friction losses, etc.), specific energy consumption in RO plants fell from 6–8 kWh/m^3 to about 3–5 kWh/m^3 [14].

As a consequence of these improvements, RO plants built or refurbished at the end of this decade reduced their energy consumption significantly. As a result of their energy efficiency in comparison to other technologies, almost all new desalination plants built in the islands this century have been RO units.

2.5. Status in 2000

By the year 2000, the water needs of more than half the population of the islands were being met through desalination which had reached a capacity of 332,000 m^3/d. Both distillation and membrane technologies were in use, although the recent trend had been to use RO for seawater. The islands had become a living laboratory for the testing of new developments. Plant capacity varied widely from below 100 to 39,000 m^3/d, and applications for product water ranged from urban supply to industrial and irrigation purposes. Brackish water production was 22,000 m^3/d [14], less than 7% of total desalination capacity and nearly half of the production in 1990 (39,000 m^3/d). These figures show a downward trend for the brackish water production due to the lack of underground water.

Table 4 shows how energy consumption fell for the different desalination technologies from the first units to the newest ones.

Table 5 shows desalinated water production for the year 2012 per island, the percentage that it represents of total water consumption and its energy consumption as a percentage of total electricity demand. The energy consumption was calculated considering an average consumption of 5 kWh/m^3 [15].

The importance of desalination varies from island to island. La Palma, for example, has no desalination plant, whereas in

Table 3
Economy ratio of distillation plants.
Source: [12].

Name of plant	Island	Year	Capacity (m^3/d)	Technology	ER	Brine max. T (C)
Las Palmas I	Gran Canaria	1969	20,000	MSF	5.8	90
Lanzarote I	Lanzarote	1975	5,000	MSF	10	120
Las Palmas II	Gran Canaria	1979	18,000	MSF	9.68	120
Cotesa	Tenerife	1994	3,600	ME	10.7	70
Las Palmas-Telde	Gran Canaria	2000	35,000	ME	10.95	70

Table 4
Energy consumption evolution in desalination plants.
Source: [12].

Technology	Energy efficiency measurement	Oldest plants	Newest plants
MSF	Economy ratio	5.6	9
ME	Economy ratio		11
CV	Electricity consumption (kWh/m^3)	22	8–9
RO (energy recovery: turbines)	Electricity consumption (kWh/m^3)	8–6	5–4
RO (energy recovery: isobaric chambers)	Electricity consumption (kWh/m^3)		3–2

Table 5
Desalinated water production and energy consumption per island (year 2012).

	Desalinated water production h/m^3/y[a]	Desalinated water vs total consumption (%)[b]	Energy consumption (%) [b]
Tenerife	36	16	5
Gran Canaria	128	62	19
Fuerteventura	32	80	28
Lanzarote	27	73	16
La Gomera	0	0	0
El Hierro	0.8	27	9
La Palma	0	0	0

[a] [16]
[b] Own elaboration.



Fig. 1. Evolution of desalinated water production from 1996 to 2011.
Source: [5].

Lanzarote desalinated water represents 99% of total water consumption. Total plant energy consumption is proportional to the amount of desalinated water produced and the percentage that it represents of total electricity demand also changes significantly from island to island.

The regional electricity consumption in 2000 in the Canary Islands was around 6000 GWh. The energy demand for desalination processes represented 9.5% of the total electricity demand. In 2012, the regional electricity consumption was around 9000 GWh and the percentage of electricity consumption for desalination processes was around 13%. These figures show an upward trend for the percentage of electricity demand consumed in the desalination sector.

2.6. Entering the 21st century

Fig. 1 shows the evolution of desalinated water production from 1996 to 2011.

Since 2000, all the seawater desalination plants installed in the Canary Islands have been RO plants [16]. Only a few large-sized plants have been constructed. Most of the units built (around 100 [16]) have been small- and medium-sized RO plants. Shortly after the beginning of this century, no MSF plant was any longer in use (they had been dismantled or declared out of service) and only one medium-sized ME plant was in operation [16].

RO is now the most widespread technology in the world and has superseded distillation as the technology with the highest degree of current and future implementation. From 2005 to 2008, annual worldwide contracted RO capacity increased from 2.0 million to 3.5 million m^3/d, whereas the corresponding figures for distillation processes fell from 2.0 million to 0.5 million m^3/d [17]. RO represents 61% of current installed worldwide capacity, including sea- and brackish water desalination [18].

At the end of the 70s, seawater RO plants consumed up to 20 kWh/m^3 but, thanks to membrane efficiency improvements, the use of ERDs, new materials with less friction and variable-frequency drive devices, energy consumption has been reduced drastically. Excellent specific energy consumption of 1.80 to 2.20 kWh/m^3 can be obtained in new seawater RO plants [4].

3. Improving energy efficiency in RO

The tendency in the Canary Islands is to install RO desalination plants due to its lower energy intensity. This trend is the same worldwide [10,17–20]. Given the importance of RO desalination in the Canary Islands and worldwide, this section will concentrate on energy efficiency with this technology.

The highest energy consumption in RO plants takes place in the high-pressure pump, also called the feed pump. Pump selection depends on pumping pressure needs and water flow. There are two different types of pumps installed in RO plants: positive displacement pumps and centrifugal pumps. Centrifugal pumps are the type usually installed. Positive displacement pumps are installed in small RO plants; they are more expensive, more efficient and have higher maintenance needs than centrifugal pumps [12].

There is one feed pump per RO line; a plant has as many lines as necessary to reach the design capacity. Each line has dozens of tubes and each tube usually contains 7 elements in series (it used to be 6), although some novel designs are working with 8 elements per tube [4]. Each element usually has between 12 and 15 wound membranes. The number of tubes in each line depends on the feed pump capacity which usually operates at 55–65 bar.

Two different ways of reducing energy intensity (kWh/m^3) in RO plants can be distinguished: devices aimed at recovering useful energy in the plant (ERDs) and internal improvements of the plant to reduce energy intensity in the separation process. The main function of an ERD is to improve energy efficiency by harnessing potential energy from the brine. As well as all large-medium sized RO plants, small-sized plants also now have ERDs installed.

3.1. Energy recovery devices (ERDs)

The aim of an ERD is to reduce the energy consumption of the plant and, consequently, the energy bill. Two types of ERD can be distinguished: energy recovery turbines and isobaric chambers.

3.1.1. Energy recovery turbines

This system takes advantage of the brine outlet pressure. In the first RO plants, the brine, which is high-pressured, was directly reintroduced into the seawater (after post-treatment) and the outlet pressure was wasted. The first energy recovery systems used were Francis turbines introduced in the RO units at the beginning of the 90s to take advantage of the brine outlet pressure. The turbine was mounted in the same shaft as the high-pressure pump, reducing the energy consumption of this pump. At the end of the 90s and particularly during the first decade of this century, Pelton turbines became the preferred choice because of their higher efficiency. They were installed in new plants and also used to replace old Francis turbines. Both turbine types work as reverse running pumps.

In more recent years, the tendency has been to install isobaric chambers instead of turbine-based energy recovery systems.

3.1.2. Isobaric chambers

Isobaric chambers are newer energy recovery systems. This system also takes advantage of the brine outlet pressure. There are basically two types of isobaric chambers available from various manufacturers, each operating in a slightly different way: rotary-based (Energy Recovery Incorporated –ERI– pressure exchanger) and displacement-based (Aqualing, RO Kinetics, Pressure Exchange System (PES) from Siemag, etc.). However, all of these are based on a system that uses the brine outlet pressure to increase the feed water pressure, thus reducing the energy consumption of the high-pressure pump. The high-pressured brine and the feed water are introduced in the isobaric chambers, there is a pressure exchange between the high-pressured brine and the feed water. As brine pressure is reduced feed water pressure is increased. This feed water is then introduced in the feed pump to reach the operating pressure.

3.2. Energy intensity reduction

3.2.1. Booster turbines

A booster pump is installed to increase brine pressure for a second stage incorporated to increase plant production. This system also makes use of the brine outlet pressure. The brine, after passing through the RO line, loses about 3 to 4 bar. After the first stage, the brine is introduced in the booster pump, increasing its pressure to about 70 bar (close to the highest pressure that membranes can take). Then the brine is re-introduced in a second stage (each stage is a complete line). Booster pumps are built between the first and the second stage. The brine from the first stage continues to the second stage, producing more product water. The main objective is to increase plant capacity. After installing a booster pump, the energy consumption of the plant and hence the energy bill rise but, since there is also an increase in product water, energy intensity (kWh/m^3) is reduced. Therefore, the installation of booster pumps lead to reductions in the energy consumption per cubic meter of product water.

3.2.2. Membrane replacement

In addition to ERD installation, another way of reducing energy consumption is regular membrane replacement. Usually membranes are changed at an annual rate of 5% to 8% in brackish water and 10% to 18% in seawater units. Average membrane lifetime has traditionally ranged between 5 and 8 years. Improvements to membranes are a constant challenge to the industry and are usually aimed at reducing membrane operating pressure, thereby lowering energy consumption. When new membranes able to operate at lower pressures become available in the market it can be economically beneficial to replace the older membranes.

3.3. Energy efficiency evolution in large-sized sea water RO desalination plants

Since the beginning of this century, developments in the RO large-sized segment have been centred on enlargements and the refurbishment of already existing plants. The main purpose of refurbishments is usually a reduction in energy consumption.

Table 6 shows a comparison of the technical characteristics (including energy consumption) of one large-sized RO desalination plants at the time of its inauguration in Gran Canaria, in 2006 and in 2014. The measures implemented to reduce its energy consumption were: replacement of existing with latest generation membranes, replacement of Francis with Pelton turbines and the installation of booster pumps. The recovery ratio in Table 6 is an expression of the relationship (in percentage terms) between product and feed water flow.

The Las Palmas III–IV desalination plant has recently incorporated different energy recovery systems based on two different types of isobaric chambers in some lines. The types of isobaric chambers were rotary-based (Energy Recovery Incorporated –ERI– pressure exchanger) and displacement-based (DWEER). In practice, this means that some lines in the plant have Pelton turbines, some ERIs and others DWEER. Total energy consumption of the plant was reduced to 3 kWh/m^3 in 2014. Table 7 shows energy consumption in each of the 10 lines of the plant. It can be observed that lines 1 to 2 and 4 to 7, which incorporate isobaric chambers,

Table 6
Energy consumption evolution in the desalination plant Las Palmas III–IV.
Source: [21].

Technical characteristics	Las Palmas III–IV desalination plant		
	Initial state, 1989	2006	2014
Nominal production (m^3/day)	36,000	80,300	86,000
Number of production lines	6	10	10
Recovery ratio (%)	45	52	52
Number of elements per pressure vessel	6	6	6
Energy intensity, kWh/m^3 [a]	6.16	5.2	4.1
Energy recovery turbines	Francis	Pelton	Pelton
Number stages	2	2	2
Booster pumps (units)	No	10	12

[a] Including product water pumping for its distribution up to 200 m altitude.

Table 7
Energy consumption in the desalination plant Las Palmas III–IV (2014).
Source: [21].

Line	Production (m^3/d)	Energy recovery system	Energy intensity (kWh/m^3)
1	9500	DWEER	2.30
2	9500	ERI	2.27
3	8500	Pelton turbine	3.60
4	10 000	ERI	2.90
5	7500	ERI	2.81
6	8000	ERI	
7	10 000	ERI	2.90
8	8000	Pelton turbine	3.80
9	7500	Pelton turbine	3.85
10	7500	Pelton turbine	
Total	86 000		3

have lower energy intensity (ranging from 2.27 to 2.9 kWh/m^3) than the other lines (ranging from 3.6 to 3.85 kWh/m^3) equipped with Pelton turbines. The last line refurbished was line 2 (from Pelton to ERI). This line shows the lowest energy intensity. These figures in Table 7 indicate an average energy efficiency improvement of 40% replacing Pelton turbines by isobaric chambers.

3.4. Energy efficiency evolution in small and medium-sized desalination plants

3.4.1. Seawater

In the Canary Islands, the small- and medium-sized seawater desalination segment is completely covered by RO plants. These plants have tended to incorporate the same energy efficiency measures as the large-sized plants, especially the isobaric chambers.

After more than a decade using pressure exchange systems in RO plants, the maturity of this technology has enabled a steady reduction in the specific energy consumption of RO processes. Novel systems regularly enter the market, achieving better efficiencies and lengthening equipment lifetime. The challenge is to break the barrier of 2.0 kWh/m^3 in medium and large capacity plants. To date, this can only be achieved in small- or medium-sized facilities, provided that other high efficiency elements, such as efficient high-pressure pumps (efficiencies higher than 90%) and modern variable-frequency drive devices [4], have been installed in addition to ERDs. Note that this barrier of 2.0 kWh/m^3 is already not so far away from the theoretical minimum energy required to desalt seawater, estimated in 0.77 kWh/m^3 using the van't Hoff formula for seawater (33,000 ppm salinity at 25 °C) [22].

Other innovations leading to slight reductions in energy consumption include the installation of latest-generation electronic variable frequency drives to start and adjust the engine speed of the intake, high pressure and booster pumps. Previously, as engine start-up was direct, very complex and could not be regulated, they could only be operated at their nominal operation level [4].

3.4.2. Brackish water

The brackish water segment is divided into reverse osmosis (RO) and electrodialysis (ED) plants with a preference in recent years for RO plants. There are 18 ED units in operation compared to more than 100 RO plants. The installed capacity of ED plants is about 65,000 m^3/d versus approximately 85,000 m^3/d in RO plants [16]. This difference between number of plants and capacity is due to plant size. ED plants are usually bigger than RO plants and all the large-sized brackish water plants are ED units. Energy consumption in ED units depends heavily on water salinity, varying from 1 to 3 kWh/m^3, sometimes even less [12].

4. Conclusions

The answer to water scarcity in the Canary Islands has been, to a large extent, desalination. From the first desalination plant back in 1964 to the present time, desalination capacity has risen beyond 600,000 m^3/d. However, the major handicap with desalination has been its high energy consumption. In a region with an external energy dependency of 98%, where oil needs to be shipped in and where desalination accounts for nearly 12% of electricity consumption, energy efficiency in desalination processes is crucial. Though all main types of desalination technology have historically been employed in the Canary Islands, the demand for efficiency means that only RO systems are presently being installed for new seawater plants and only RO or ED plants for brackish water plants. Brackish water desalination plants represent nowadays just a minor part of the desalination production in the Canary Islands.

Major efforts have been made in medium- and large-sized seawater RO plants to improve energy intensity, with a consequent reduction from about 8 kWh/m^3 in the 70s to around 2 kWh/m^3 in 2012. This gradual reduction in energy consumption was achieved initially as a result of the incorporation of recovery turbines, higher efficiency pumps and subsequently, today's state-of-the-art technology, isobaric chambers. Operating desalination plant data indicate an average energy efficiency improvement of 40% replacing Pelton turbines by isobaric chambers. This latter technology is currently employed in RO plants of all sizes. In addition, other measures such as the introduction of booster pumps and membrane improvements have also helped to achieve lower energy consumption.

The challenge is to break the barrier of 2.0 kWh/m^3 in medium and large capacity plants. To date, this can only be achieved in small- or medium-sized facilities, provided that other high efficiency elements, such as efficient high-pressure pumps and latest-generation electronic variable frequency drives, have been installed in addition to ERDs.

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